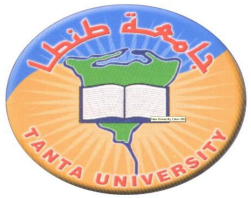


EEC 4230 - Mobile Communication Systems

Dr. Hussein Seleem, PhD

Electronics Engineering and Electrical Communications Department
Faculty of Engineering, Tanta University, Tanta, Egypt

Lecture 2: The Celluar Radio

Outline

1. Introduction
2. Frequency Reuse
3. Handoff
4. Interference and System Capacity

Introduction

Early mobile radio systems:

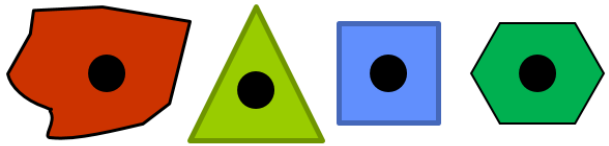
- It Achieved a large coverage area by using a single, high-powered transmitter (TX) mounted on a tall tower.
- It achieved very good coverage, but it is impossible to reuse the same frequencies throughout the coverage area, since this would result in interferences.
- The system capacity (# of users serviced) is small.

The cellular concept:

- Offered a very high capacity in a limited spectrum allocation by using many low power TXs, each providing coverage to only a small portion of the service area (the **cell**).
- Each cellular base station (BS) is allocated a frequency band (group of channels) to be used within its cell.

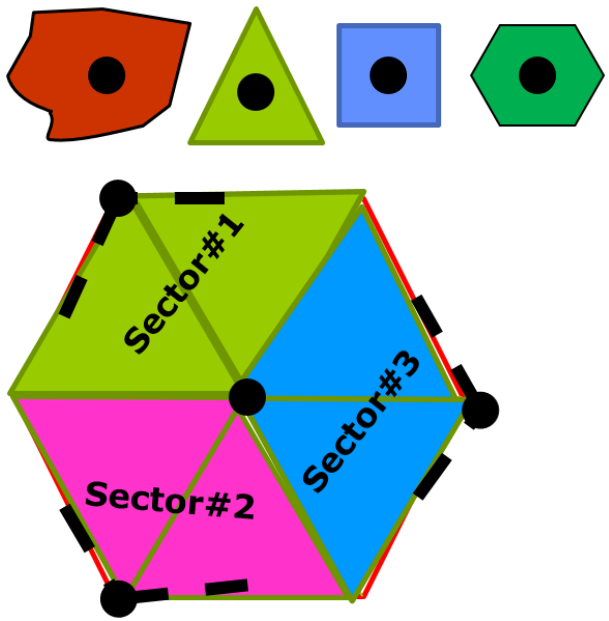
Cell Geometry

- The actual coverage of a cell is **amorphous**.
- Possible cell shapes: **circle**, **triangle**, **sq.**, **hexagon**
- BS antennas are designed to approximate the desired coverage geometry for a cell.
- Hexagonal shape is widely used (**no gaps**).
- The actual radio coverage of a cell (called **footprint**) is determined through field measurements or propagation prediction models.



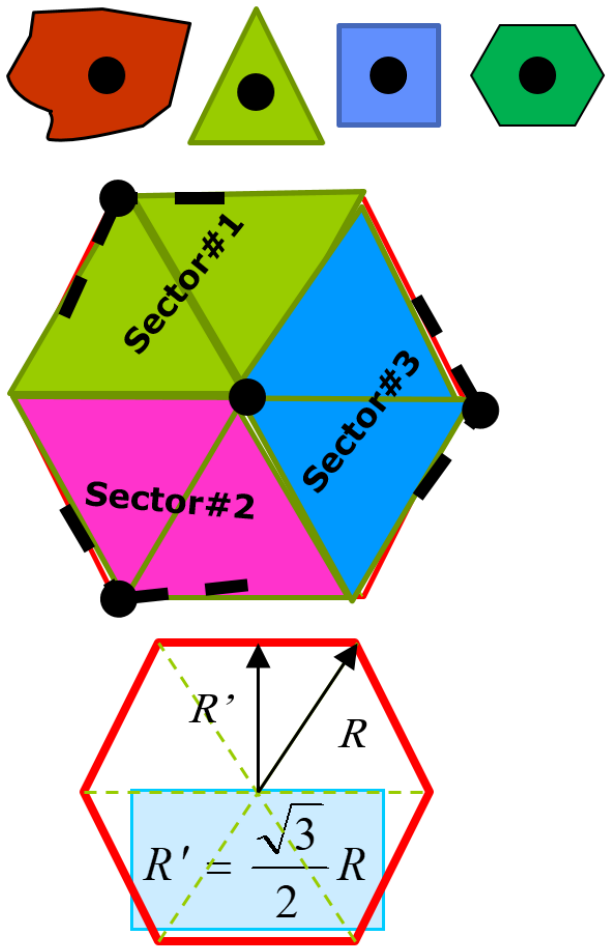
Cell Geometry

- The actual coverage of a cell is **amorphous**.
- Possible cell shapes: **circle**, **triangle**, **sq.**, **hexagon**
- BS antennas are designed to approximate the desired coverage geometry for a cell.
- Hexagonal shape is widely used (**no gaps**).
- The actual radio coverage of a cell (called **footprint**) is determined through field measurements or propagation prediction models.
- BS transmitters can be either at the center of the cell (omni-directional antennas for center-excited cells) or on 3 of the 6 cell vertices (sectored directional antennas for edge-excited cells).



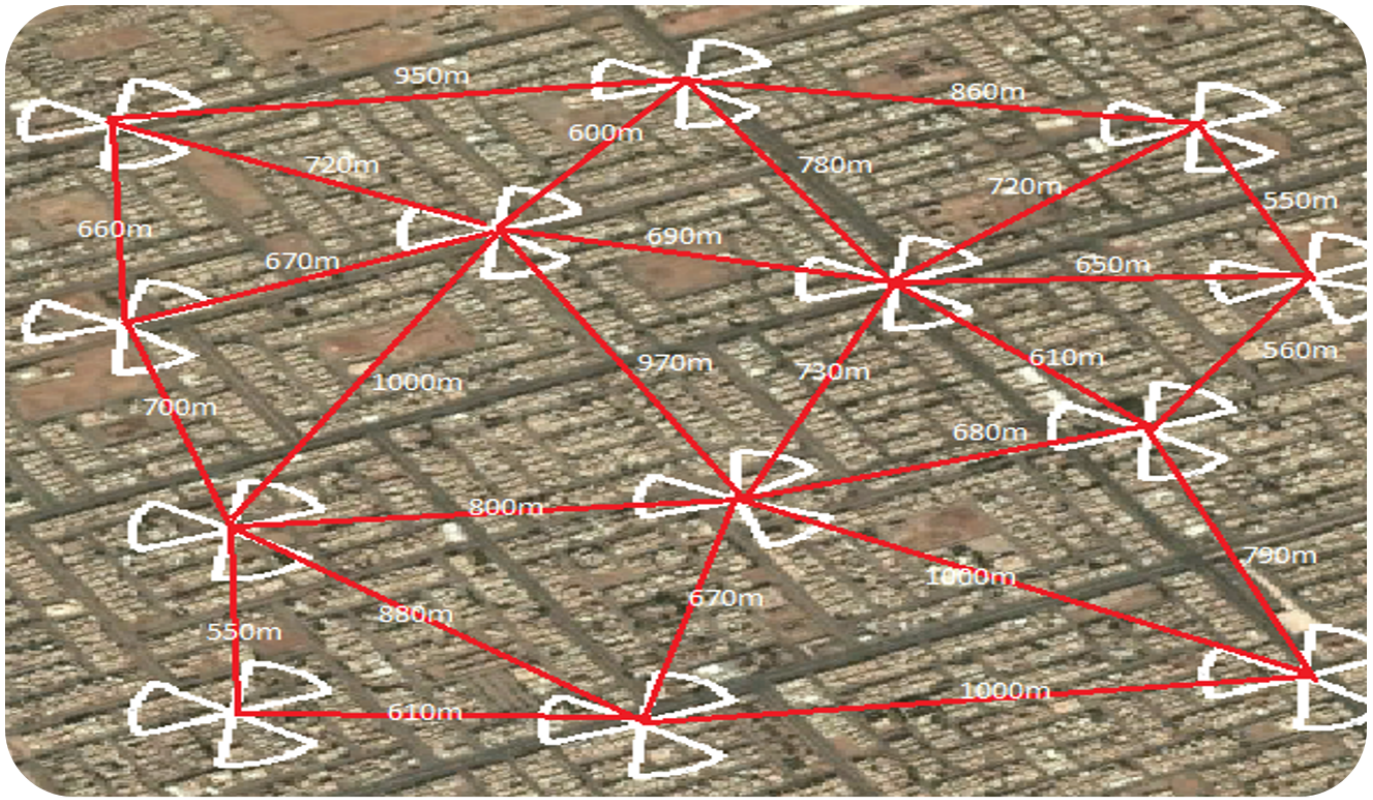
Cell Geometry

- The actual coverage of a cell is **amorphous**.
- Possible cell shapes: **circle**, **triangle**, **sq.**, **hexagon**
- BS antennas are designed to approximate the desired coverage geometry for a cell.
- Hexagonal shape is widely used (**no gaps**).
- The actual radio coverage of a cell (called **footprint**) is determined through field measurements or propagation prediction models.
- BS transmitters can be either at the center of the cell (omni-directional antennas for center-excited cells) or on 3 of the 6 cell vertices (sectored directional antennas for edge-excited cells).
- Cell radius R is the distance between cell center and the vertex of the hexagon
- Surface Area of hexagon is given by: $\frac{3\sqrt{3}}{2}R^2$



Example of BS Deployments

Example of BS Deployments



Typical planning diagram by one of the operator from his network, cell radius < 500m (half of the site-to-site distance)

Example of BS Deployments

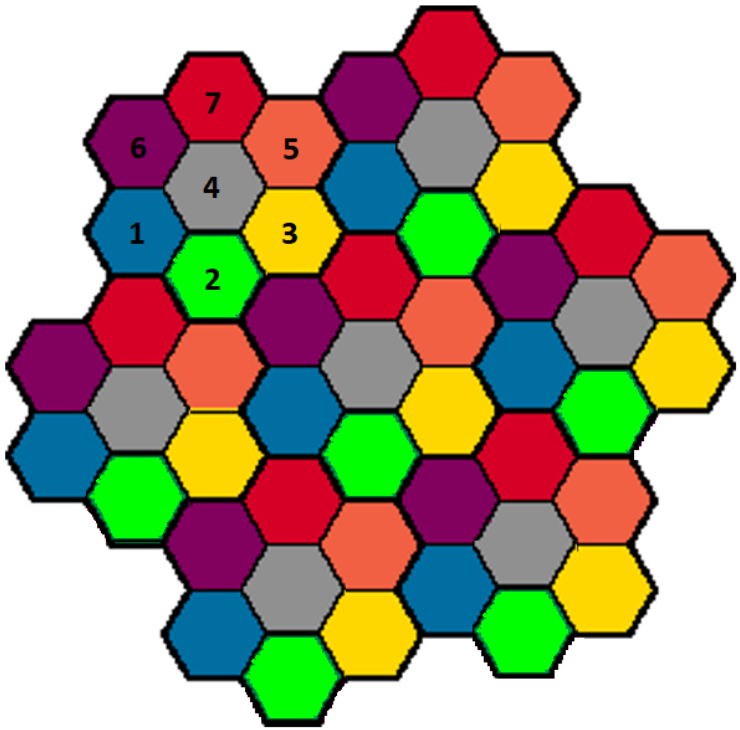
Typical RF Coverage Patterns:

- **2G/3G/4G**: RF coverage in microwave bands ($f_c = 900$MHz) is more amorphous, many coverage holes at cell-edge. Typical problems in 2G/3G/4G.
- **5G in 28GHz & 38GHz**: RF coverage in mmWave bands is less amorphous, less coverage holes than microwave.

This is done by one of the simulator by one of the operator to simulate the RF coverage for Trisector BSs.

Frequency Reuse

- High capacity is achieved in cellular systems by limiting the coverage of each BS transmitter to a small geographic area called a **cell**, Therefore the same radio channel may be used by another BS located some distance away. This is called **frequency reuse**.
- Available channels are assigned to a small number of neighboring BSs (**clusters**). BSs in a cluster are assigned different groups of channels to **minimize interference**.
- Clusters can be reused many times throughout the coverage area, as long as the interference between co-channel stations is kept below an acceptable level.



Coverage area with cluster size $(N) = 7$

Frequency Reuse: Definitions

Cluster

The N cells which collectively use the complete set of S available frequencies, $S = kN$ where k is the number of channels per cell.

The Cellular System Capacity

If the cluster is replicated M times within the entire cellular system, then the total number of channels used (the system capacity) is $C = MS = MkN$

Reuse Factor

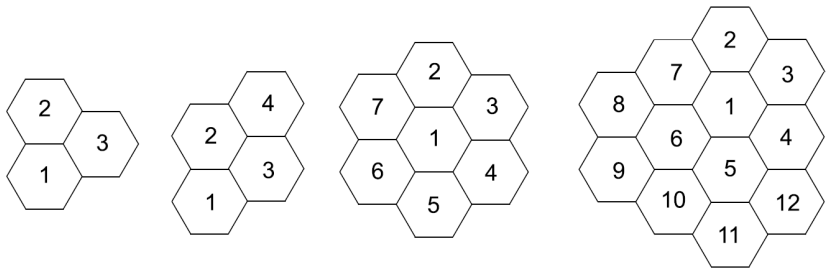
The frequency reuse factor is $F = \frac{1}{N}$

Because of the hexagonal geometry used, there are only certain cluster size, N, that can be used, e.g. $N = 4, 7, 12$, etc, in order to be able to reuse cells without replicating adjacent cells or leaving gaps between them.

Frequency Reuse

Mathematically, N can only have values satifying the equations: $N = i^2 + ij + j^2$ where i and j are nonnegative integers.

i	1	2	2	3	2	...
j	1	0	1	0	2	...
N	3	4	7	9	12	...



Hexagonal tessellation and channel grouping for $N = 3, 4, 7, 12$

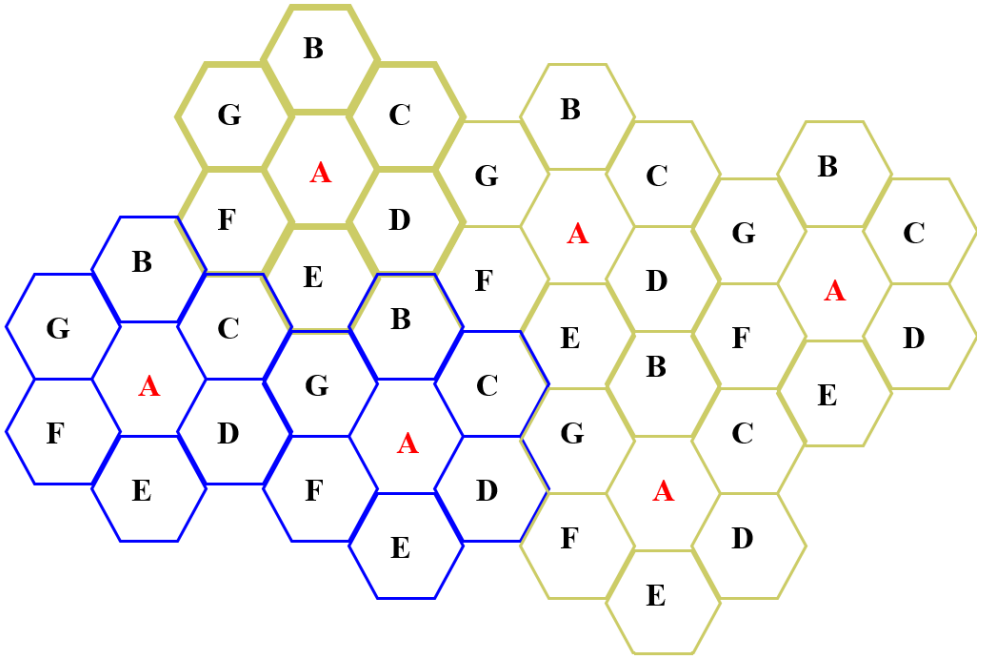
Cellualr design is at the cluster level. therefore, once cluster is designed and finalized we simply repeate it all over the coverage area.

Frequency Reuse

Mathematically, N can only have values satifying the equations: $N = i^2 + ij + j^2$ where i and j are nonnegative integers.

Example: 1

i	1	2	**2**	3	2	...
j	1	0	**1**	0	2	...
N	3	4	**7**	9	12	...



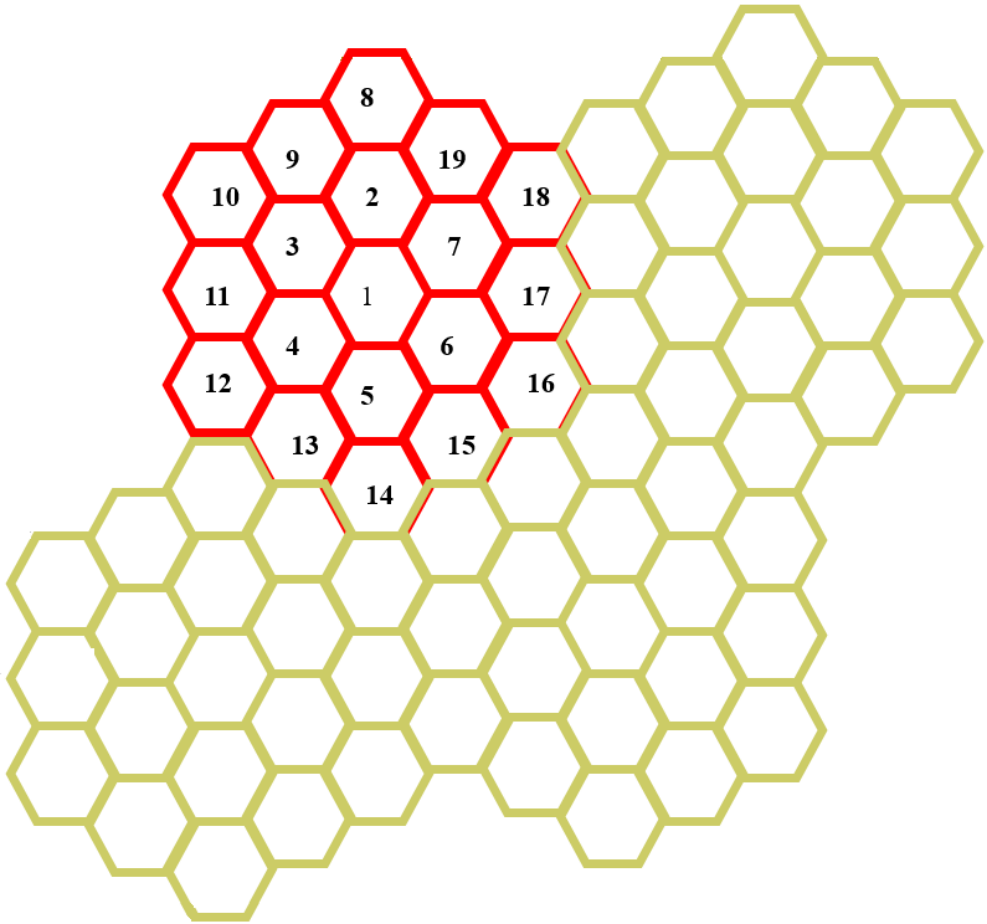
Coverage area with cluster size $N = 7$

Frequency Reuse

Mathematically, N can only have values satifying the equations: $N = i^2 + ij + j^2$ where i and j are nonnegative integers.

Example: 2

i	1	2	...	**3**	...
j	1	0	...	**2**	...
N	3	4	...	**19**	...



Coverage area with cluster size $N = 19$

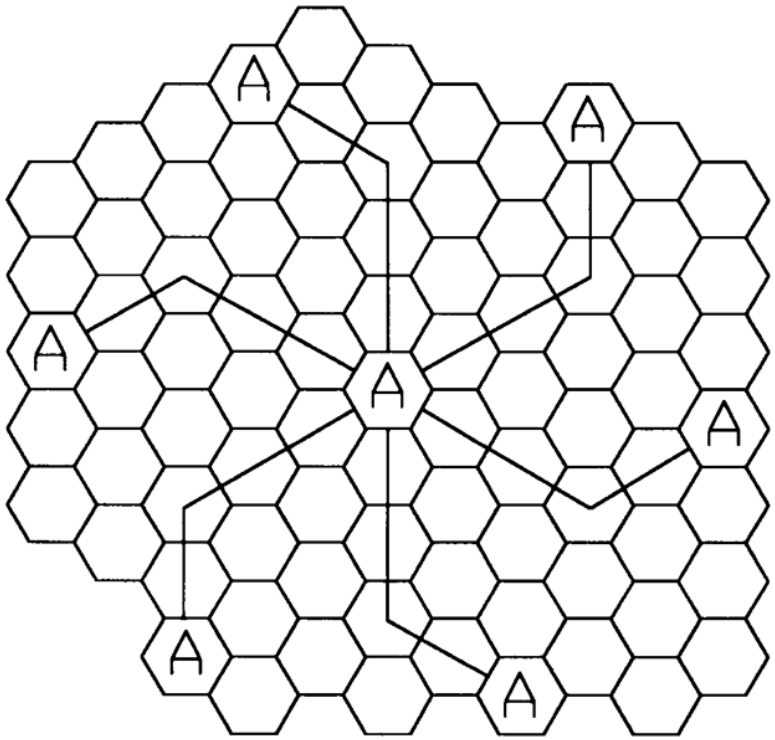
Frequency Reuse

Locating co-channel cells:
To find the nearest co-channel neighbors of a particular cell:

- Move i cells along any chain of hexagons
- Then turn 60^o anti-clockwise and move j cells.

Example: 2

i	1	2	...	**3**	...
j	1	0	...	**2**	...
N	3	4	...	**19**	...



Locating co-channels, $N = 19$

Frequency Reuse: Exercise

Ex. 1

A total bandwidth of 33 MHz is allocated to a cellular system, which uses **two** 25 kHz simplex channels to provide full duplex voice and control channels:
(i) Assume that the system uses a 4-cell reuse pattern, what is the # of channels available per cell
(ii) If 1MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control and voice channels.

Frequency Reuse: Exercise

Ex. 1

A total bandwidth of 33 MHz is allocated to a cellular system, which uses **two** 25 kHz simplex channels to provide full duplex voice and control channels:
(i) Assume that the system uses a 4-cell reuse pattern, what is the # of channels available per cell
(ii) If 1MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control and voice channels.

Ans.

One duplex Ch=50kHz, Total Ch available=33MHz/50kHz = **660 duplex Ch.**
(i) Note that $N = 4$, Ch per cell=660/N = **165 Ch.**
(ii) The # of control ch= 1MHz/50kHz = **20 Ch**, thus assign **5 control Ch per cell**, The # of voice ch per cell=640/N=**160 Ch.**

Frequency Reuse: Exercise

Ex. 1

A total bandwidth of 33 MHz is allocated to a cellular system, which uses **two** 25 kHz simplex channels to provide full duplex voice and control channels:
(i) Assume that the system uses a 4-cell reuse pattern, what is the # of channels available per cell
(ii) If 1MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control and voice channels.

Ans.

One duplex Ch=50kHz, Total Ch available=33MHz/50kHz = **660 duplex Ch.**
(i) Note that $N = 4$, Ch per cell=660/N = **165 Ch.**
(ii) The # of control ch= 1MHz/50kHz = **20 Ch**, thus assign **5 control Ch per cell**, The # of voice ch per cell=640/N=**160 Ch.**

Ex. 2

Repeat Ex. 1 for cases: $N = 7$, $N = 12$.

Frequency Reuse: Channel Assignments

Fixed channel assignments:

Each cell is allocated a fixed set of voice channels (see Ex.1). Users can be served only by the available channels in the cell. If all channels are occupied, the call is blocked.

Dynamic channel assignments:

Cells are not pre-allocated sets of voice channels. Instead, each time a call request is made, the MSC allocates a channel to the requesting cell. Likelihood of blocking is reduced, but MSC needs real-time data on channel occupancy, traffic distribution, and signal power. This increases the storage and computational load.

Hybrid channel assignments:

Each cell is allocated a predetermined set of voice channels. A cell can borrow channels from a neighboring cell if all its channels are already occupied. The MSC supervises the borrowing procedures.

Handoff

handoff

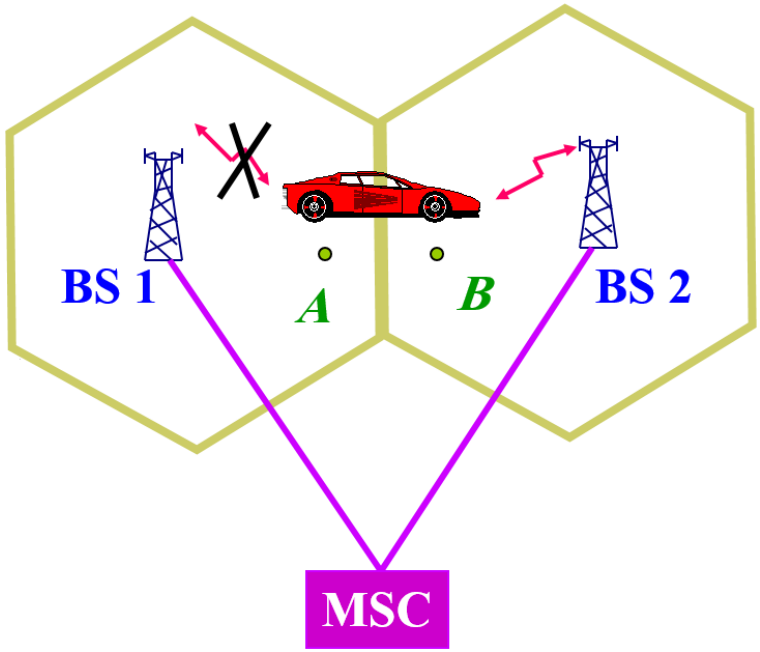
A change of radio resource from one cell to adjacent cell when a mobile travels beyond the coverage region of its serving BS, it must be transferred to better BS.

If the received power drops too low prior to handoff, the call is "dropped".

Therefore,

Handoff must be done:

(1) successfully (2) only when necessary
(3) quickly (power may go down quickly)
(4) imperceptible to users



Signal strength varies quickly due to fading, but we are interested in short-term average power. So, MSC uses average power to decide when to HO, rather than instantaneous

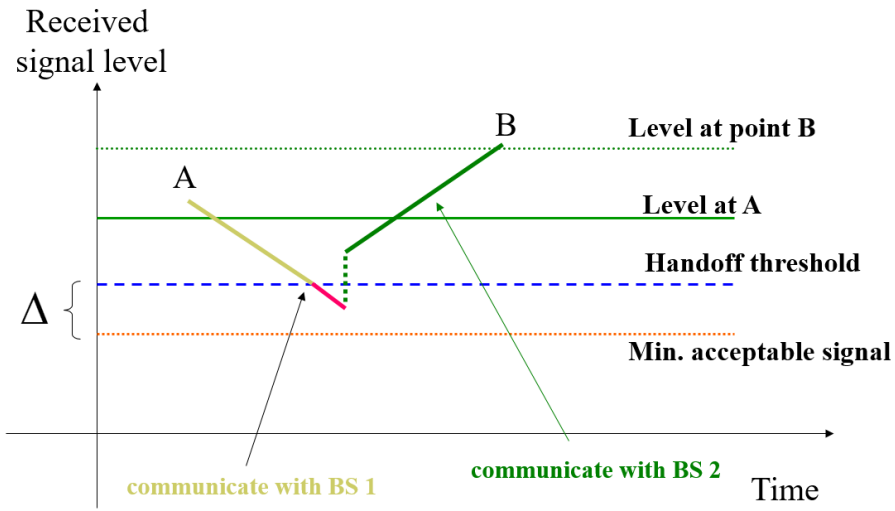
Handoff

handoff

$$P_{r,handoff} = P_{r,min\ useable} + \Delta$$

$P_{r,handoff}$: Optimal signal level, at which a handoff is initiated (Handoff threshold).
$P_{r,min\ useable}$: Min acc power, below which a call can't be rxed.
Δ: Handoff margin.

- if Δ is too large, unnecessary HO may occur.
- if Δ is too small, there may be insuffiient time to complete a HO before a call is lost because of week signal conditions.



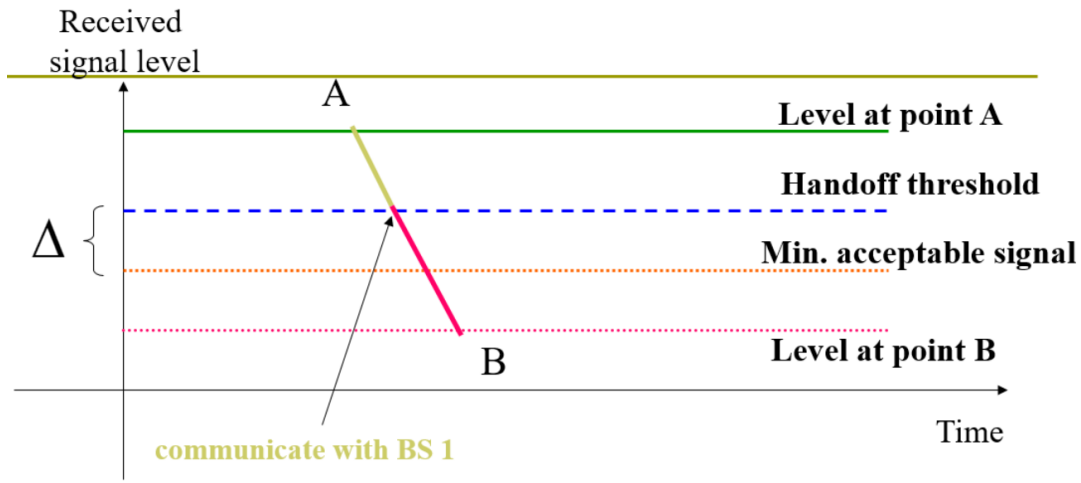
Successful handoff

In GSM, HO is typically within 1-2 sec. In AMPS, this was 10 sec.

Handoff

This may happen if:

- Δ is very small
- The mobile moves very fast
- There is an excessive delay (by the MSC)



Failed handoff

Handoff

Ex. 2

Let the speed of a mobile be $v = 35$ m/sec. For $n = 4$, a cell radius of 500 m (the distance at which the power is at the threshold), and a 2 sec handoff, what is Δ is needed?

Handoff

Ex. 2

Let the speed of a mobile be $v = 35$ m/sec. For $n = 4$, a cell radius of 500 m (the distance at which the power is at the threshold), and a 2 sec handoff, what is Δ is needed?

Sol.

Consider the received power at the two times:

$$P_{r,min\ useable} = P_0 - 10n \log_{10} d$$

$$P_{r,handoff} = P_0 - 10n \log_{10}(d - 70)$$

Taking the difference of the two equations:

$$\Delta = 10n \log_{10} \frac{d}{d - 70}$$

As the call is dropped at d=500m we have $\Delta = 2.6$ dB.

Handoff Strategies in Modern Cellular Systems

Hard HandOff (HHO)

That is described previously. MS maintains link only with one BS at a time.

Soft HandOff (SHO) (MSC controlled)

- All BSs measure all the signals from a MS, using a spare "locator receiver". Then it decide when to handoff.
- SHOs are used in CDMA-based cellular (IS-95, CDMA2000), where all BS use the same frequency.

Mobile-Assisted HandOff (MAHO)

- MSC no longer monitors signal strength, mobiles themselves measure the signal from neighboring BSs and reports this to the MSC.
- This ends up leading to Faster HO process!
- Used in digital cellular systems (2G/3G+).

Interference and System Capacity

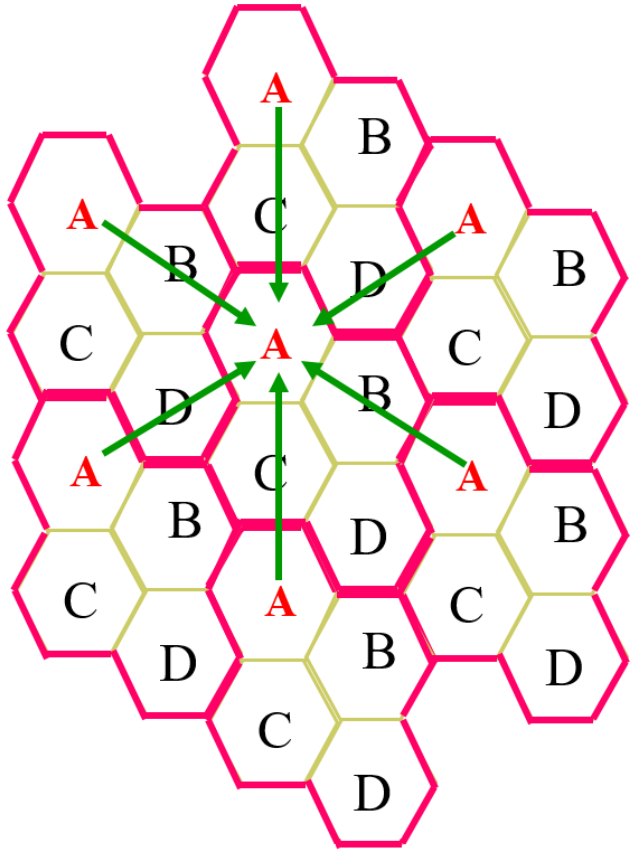
Interference is the major limiting factor in the performance of cellular systems.
Two major types of system-generated interferences:

- Co-channel interference (CCI)
- Adjacent channel interference (ACI)

Interference and System Capacity

Interference is the major limiting factor in the performance of cellular systems.
Two major types of system-generated interferences:

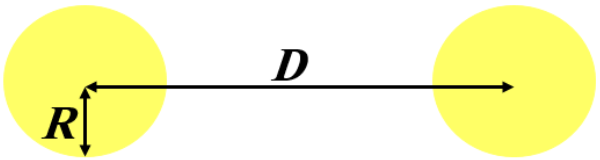
- Co-channel interference (CCI)
- Adjacent channel interference (ACI)



Co-channel Interference (CCI) for 4-cell reuse pattern ($N = 4$)

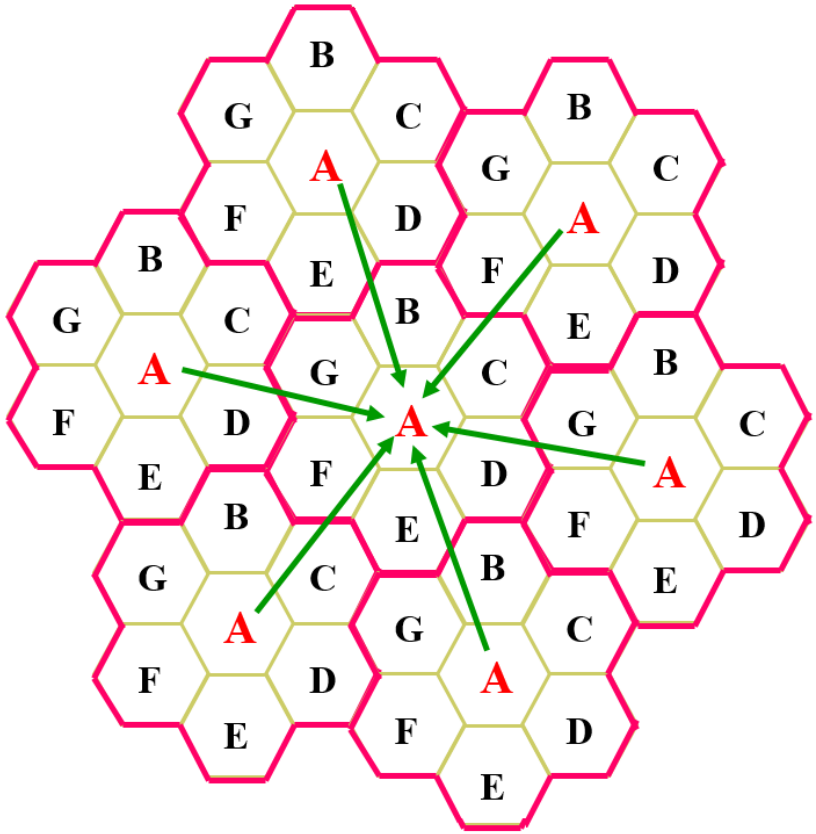
Co-channel Interference (CCI)

- Every BS A uses f_A.
- Every BS B uses f_B.
- ....



Co-channel reuse ratio $Q = \frac{D}{R}$

R: The radius of a cell
D: The distance between the center of the cell and the nearest co-channel cells.
In a hexagonal geometry: Q is related to the cluster size N as: $Q = \sqrt{3N}$ – **proof!**



Co-channel Interference (CCI) for 7-cell reuse pattern ($N = 7$)

Co-channel Interference (CCI)

Trade-off:

Small value of Q provides larger capacity (since cluster size N is small)

Large values of Q improves the transmission quality (since CCI is reduced due to increase in D/R ratio

i	1	2	2	3	2	3
j	1	0	1	0	2	1.
$N = i^2 + j^2 + ij$	3	4	7	9	12	13
$Q = \sqrt{3N}$	3	3.46	4.58	5.2	6	6.24

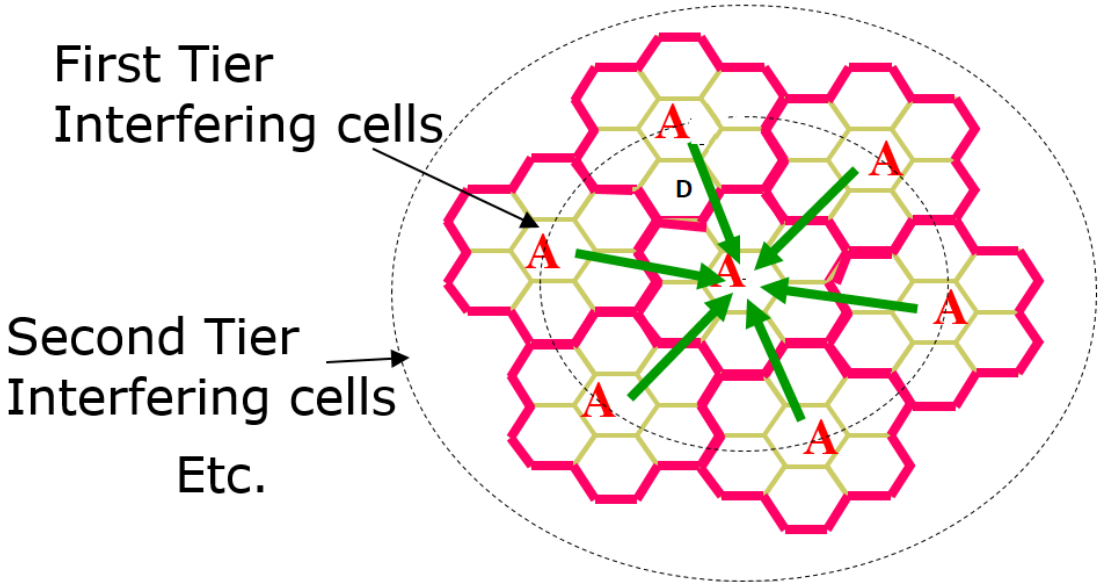
Signal to interference Ratio (SIR), S/I

Assume that we have i_0 co-channel interfering cells on a mobile. The SIR can be expressed as:

$$SIR = \frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$

S: is the desired signal power (from the desired BS)
I_i: is the i^{th} interfering signal power (from co-channel BS)

The average received signal power can be expressed as: $P_{rec} = P_0(\frac{d}{d_0})^{-n}$
d: distance between the RX and the TX.
n: is the PLE, typically $2 \leq n \leq 4$, in urban areas,
d_0, P_0 are reference constants.



Worst Case SIR (Rough Approximation) (Assume Mobile at cell edge)

If the mobile is at a distance R from its own BS and distance D_i from the i_{th} co-channel BS_i, then

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} D_i{}^{-n}}$$

If we consider only the first layer of interfering cells, and if we assume that they are of equal distance D from the mobile, then

$$\frac{S}{I} = \frac{R^{-n}}{i_0 D_i{}^{-n}} = \frac{1}{i_0}\left(\frac{D}{R}\right)^n = \frac{1}{i_0} Q^n = \frac{1}{i_0}(\sqrt{3N})^n$$

$$\frac{S}{I}[\text{dB}] = -10\times\log_{10}(i_0)+10\times n\times\log_{10}(\sqrt{3N})$$

Ex.1

For the US AMPS cellular system which uses FM and 30kHz channel, field tests have shown that sufficient voice quality is provided when SIR >18 dB. If $n = 4$, find the minimal cluster size N for the system.

Ans

For 4-cell reuse ($N = 4$):
$\frac{S}{I}[\text{dB}] = 13.8 \text{ dB} < 18 \text{ dB}$
For 7-cell reuse ($N = 7$):
$\frac{S}{I}[\text{dB}] = 18.66 \text{ dB} > 18 \text{ dB}$

So a minimum cluster size of $N = 7$ is required to achieve SIR >18 dB.

Worst Case SIR (Exact Geometry) (Assume Mobile at cell edge)

For $N = 7$

Again assume that the mobile at the cell boundary, the mobile is at distance $(D - R)$ from two nearest co-channel cells, $(D + R/2)$, D, $D - R/2$, and $D + R$, from the remaining co-channel cells in the first tier.

The worst case SIR can be expressed as:

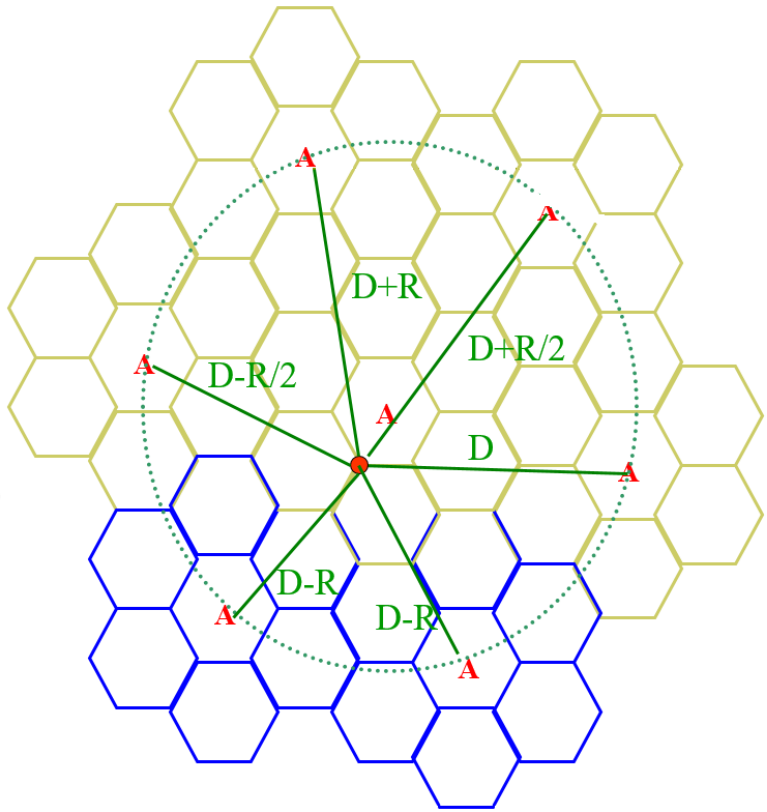
$$\frac{S}{I} = \frac{1}{2(Q-1)^{-n}+(Q)^{-n}+(Q+\frac{1}{2})^{-n}+(Q+1)^{-n}+(Q-\frac{1}{2})^{-n}}$$

Ex. 2

For SIR>18 and $n = 4$, find the min cluster size N.

Ans

$N = 7$ –> $Q = 4.58$ –> SIR[dB] =16.86 <18 dB.
$N = 9$ –> $Q = 5.20$ –> SIR[dB] =19.40 >18 dB.



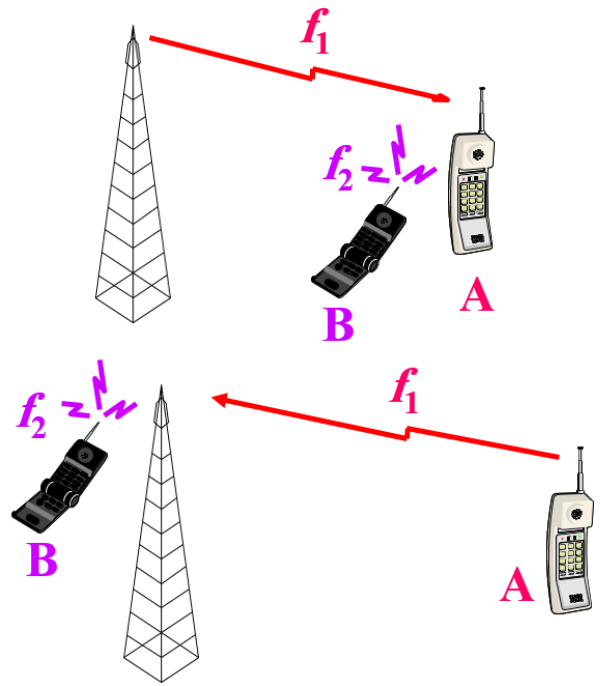
Adjacent channel interference (ACI)

It results from signals which are adjacent in frequency to the desired signal. Due to imperfect receiver filters which allow nearby frequencies to leak into the passband.

Near-far effect:

1. When an adjacent channel user is transmitting in very close range to a subscriber's RX, while the RX attempts to receive a BS on the desired channel.
2. When a mobile close to a BS transmits on a channel close to one being used by a weak mobile.

CCI is a design problem, while ACI is a problem due to imperfections in implementation.



Adjacent channel interference (ACI)

How to minimize the ACI?

- Optimum filtering.
- Careful channel assignment: Keep the frequency separation between channels in a given cell as large as possible. To achieve this, sequentially assign successive channels in the frequency band to different cells (N channel bandwidth separation will be achieved in an N-cell reuse system).
- Power control: In practical cellular system, BS controls power levels transmitted by subscribers to ensure that mobiles transmit the smallest power necessary to maintain good quality. This preserves battery life and reduces interference on the reverse channels (near-far effects reduced).